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A Comprehensive Assessment of Stream Fragmentation in Great Britain

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Abstract

Artificial barriers are one of the main threats to river ecosystems, resulting in habitat fragmentation and loss of connectivity. Yet, the abundance and distribution of most artificial barriers, excluding high-head dams, is poorly documented. We provide a comprehensive assessment of the distribution and typology of artificial barriers in Great Britain, and estimate for the first time the extent of river fragmentation. To this end, barrier data were compiled from existing databases and were ground-truthed by field surveys in England, Scotland and Wales to derive a correction factor for barrier density across Great Britain. Field surveys indicate that existing barrier databases underestimate barrier density by 68%, particularly in the case of low-head structures (<1 m) which are often missing from current records. Field-corrected barrier density estimates ranged from 0.48 barriers/km in Scotland to 0.63 barriers/km in Wales, and 0.75 barriers/km in England. Corresponding estimates of stream fragmentation by weirs and dams only, measured as mean barrier-free length, were 12.30 km in Scotland, 6.68 km in Wales and 5.29 km in England, suggesting the extent of river modification differs between regions. Our study indicates that 97% of the river network in Great Britain is fragmented and less than 1% of the catchments are free of artificial barriers.

Keywords: instream infrastructure, stream barriers, connectivity, rivers, obstacle inventory, dams

1. Introduction

Maintaining river connectivity is an essential requirement for the effective functioning of river ecosystems and a crucial component to achieving ‘good ecological status’ according to the Water Framework Directive (Directive 2000/60/EC; EC, 2000). However, river connectivity can be disrupted by instream infrastructure, which can alter hydro-geomorphological processes, temperature regimes and sediment loadings, ultimately impacting on the movement of organisms, nutrients and biologically-mediated energy flow through river systems (Petts, 1980; Köster et al., 2007; Nyqvist et al., 2017; Rincón et al., 2017; Birnie-Gauvin et al., 2018).

The spatial distribution of barriers in a catchment determines, to a large extent, their impacts on sediment fluxes (Petts and Gurnell, 2005; Schmitt et al., 2018b), fluvial habitats such as floodplains and deltas (Schmitt et al., 2018a), and abundance and diversity of freshwater biota (Cooper et al., 2017; Rincón et al., 2017; Van Looy et al., 2014). Barriers situated in lowlands can exert significant impacts throughout the catchment (Rolls, 2011), for example by reducing the habitat suitable for rheophilic fish, and by preventing or delaying fish migrations (Birnie-Gauvin et al., 2017; De Leeuw and Winter, 2008; Harding et al., 2017). Headwater barriers, on the other hand, can impact fish populations that may be already isolated by steep gradients and natural falls (Whiteley et al., 2010), but that can become more vulnerable to habitat fragmentation by the addition of artificial barriers (Compton et al., 2008). Headwater barriers can alter downstream flows and sediment transport, which can trigger changes in turbidity (Bond, 2004; Crosa et al., 2010; Quinlan et al., 2015) and impact on the abundance and diversity of fish and macrophytes (Benejam et al., 2016; Gomes et al., 2017). Barrier placement also plays a role in determining impoundment size (Van Looy et al., 2014), which is known to influence fish migration (e.g. Keefer and Caudill, 2016; Nyqvist *et al.*, 2017).

In addition to barrier location, barrier height also plays a major role in determining barrier impacts on freshwater biota and the surrounding ecosystem (Bourne et al., 2011; Frings et al., 2013; Holthe et al., 2005; Kemp and O'Hanley, 2010; Meixler et al., 2009; Rolls et al., 2013). For example, high-head structures, typically those above 8 m (USACE, 2000) or 15 m high (WCD, 2000), often create impoundments greater than 3×10^6 m^3 (WCD, 2000) that are prone to thermal stratification and changes in pH, which can cause shifts in community composition within the reservoir as well as downstream (Muth et al., 2000; Ward and Stanford, 1979). Low-head structures can also impact on essential ecological processes just as strongly (Fencl et al., 2015; Garcia de Leaniz, 2008; Gibson et al., 2011; Hohensinner et al., 2004; Jungwirth et al., 2000; Warren and Pardew, 1998). Whilst barrier impacts vary between barrier types (Mueller et al., 2011), low-head structures (i.e. those with a reservoir surface area typically <0.1 km^2) make up 99.5 % of the estimated 16.7 million artificial barriers present globally (Lehner *et al.,* 2011) and are likely to cause greater cumulative impacts and a more significant loss of river connectivity than high-head structures (Callow and Smettem, 2009; Mantel et al., 2017, 2010a, 2010b; Rincón et al., 2017; Spedicato et al., 2005; Thorstad et al., 2003).

In most cases, existing barrier databases are limited and incomplete, and although they list most high-head dams (>15 m high; Berga et al., 2006; Lehner et al., 2011), they tend to ignore low-head structures. Consequently, to gain an understanding of the true extent of river fragmentation, it is important to quantify barrier distribution and height, and include low-head weirs and other similar structures (Garcia de Leaniz et al., 2018; Januchowski-Hartley et al., 2019). Despite the importance of river fragmentation in determining ecosystem health, its extent in Great Britain is poorly understood (e.g. McCarthy *et al.*, 2008; Lucas *et al*., 2009; Russon, Kemp and Lucas, 2011; Gauld, Campbell and Lucas, 2013). Recent studies have focused on barriers to salmon migration in Scotland (Buddendorf et al., 2019; SEPA, 2018) and hydropower opportunities in England and Wales (Environment Agency, 2018), yet no global river connectivity assessment exists for Great Britain (Environment Agency, 2018),

Here we provide novel, ground-truthed estimates of the density, typology and spatial distribution of artificial barriers in England, Scotland and Wales using a harmonised database, and assess, for the first time, the extent of stream fragmentation across Great Britain.

2. Methods

2.1. Barrier location, type and height

We considered as ‘artificial barriers’ all anthropogenic structures that can interrupt ecological processes described by the River Continuum Concept (Vannote et al., 1980), including all structures detailed in Table 1. Data on the location, type and height of artificial barriers were obtained from the Environment Agency (EA) for England and Wales (Environment Agency, 2018), the Scottish Obstacles to Fish Migration database (SEPA, n.d.), the Global Reservoir and Dam (GRanD) database (Grill et al., 2015) and the European Environment Agency catchments and rivers network system (Ecrins) dam database (EEA, 2012). Barriers were included in the AMBER-GB database (AMBER: Adaptive Management of Barriers In European Rivers - www.amber.international) if they met stringent criteria and represented unique records. Thus, barriers were excluded and considered duplicates if they occurred within 500 m of a barrier of the same characteristics in other databases. We chose a 500 m duplicate exclusion threshold based on a pilot expert assessment, where we applied 50 m, 100 m, 500 m and 1000 m thresholds and compared the number of new records and the risk of including duplicates. The 500 m exclusion criterion only related to dams (present in all four source databases), as there was no overlap between the EA and SEPA databases. When duplicate records were identified, barrier attributes were preferentially extracted from the database with the widest spatial coverage (i.e. global database first, regional database last). For the purposes of analysis, we classified all artificial barriers into six basic types (Table 1), in line with an ongoing study at the European scale (Garcia de Leániz et al., 2018) to enable comparison with other databases globally.

2.2. Field validation of barrier data

To validate data on barrier type and location we carried out nineteen field walkover surveys, typically 20 km in length, stratified across five rivers in Wales (mean = 21.2 km), five rivers in England (mean = 16.7 km) and nine rivers in Scotland (mean = 12.6 km, Table S1, Figure S1). These rivers represent 0.2% of the total river network in Great Britain and are representative in terms of barrier siting (Bishop and Muñoz-Salinas, 2013; Forzieri et al., 2008; Rojanamon et al., 2009; Yasser et al., 2013), barrier density, stream order (Strahler, 1957), and land cover of rivers in England, Scotland and Wales. Fifth and sixth order rivers were excluded from the validation surveys as they only contribute 2.6% and 0.5% to the total stream length in Great Britain, respectively, and are well covered in existing barrier databases due to the high flood risk they pose to settlements and property (Lempérière, 2017). We used the Ecrins river network to determine sites for validation (European Catchment and Rivers network System; EEA, 2012), in line with ongoing barrier surveying at the European scale (Garcia de Leaniz et al., 2018).

River reaches surveyed for validation included upland and lowland rivers with elevation ranging from 0 m to 346 m (mean = 88.2 m, SE = 5.0) and 0.1 % to 3.7 % slopes (mean = 1.0 %, SE = 0.01). Most river reaches surveyed were single-thread channels with a sinuosity index ranging from 1.1 to 1.6 (mean = 1.3, SE = 0.01), a stream order between 1 and 4 (median = 3) and are located in CORINE landcover level 1 classes 1 to 3 (median = 2) including artificial surfaces, agricultural areas and forest and semi-natural areas. Comparisons of these reaches to all river reaches in Great Britain are available in Table S2.

2.3. Metrics of river fragmentation

We calculated two measures of river fragmentation, barrier density and barrier-free length. Barrier density was calculated for sub-catchments in the Catchment, Characterisation and Modelling (CCM) 2.1 database (median area = 5.2 km^2, interquartile range (IQR) = 0.0 - 11.9, Vogt et al., 2008) using the total number of artificial barriers (in AMBER-GB) per total river length (km, OS Open Rivers) for each sub-catchment in QGIS 3.03 (QGIS Development Team, 2018). Barrier-free length (BFL) was calculated using custom tools in ArcGIS 10.5 (ESRI, 2011) as the stream length between two consecutive barriers (or the stream length between a barrier and the river source or mouth) using weirs and dams only, as these were the dominant barrier types and could be compared across all databases. Comparisons of barrier density between field data and existing databases, and between regions (England, Scotland and Wales), were tested by a paired t-test and an Analysis of Variance, respectively; a log10 transformation was applied to barrier height, barrier density and BFL to reduce skew and meet model assumptions, which were checked via residual diagnostic plots in R 3.5.2 (R Core Team, 2018).

2.4 Sensitivity analysis and barrier discovery rate

We used a bootstrap approach (Chao et al., 2013) to assess the influence of distance surveyed on barrier discovery rate, and hence estimate the density of new barriers per river length. For this, we randomly resampled with replacement (10,000 times each) between 1 and 19 samples from the total set of 19 field validation catchments, calculated the mean barrier density and bootstrapped 95% CI of new barriers discovered per km, as a function of the total river length surveyed. We carried out separate bootstrap resampling estimates for England, Scotland and Wales, but as these overlapped widely, we provide a single sensitivity analysis across Great Britain.

3. Results

3.1. Abundance and typology of artificial barriers

We compiled a harmonised new barrier database for Great Britain (AMBER-GB) consisting of unique records of 19,053 artificial barriers in England, 2,128 in Scotland and 2,437 in Wales from existing databases (total = 23,618), as part of the EU-funded AMBER project (Supplementary Material, Table 1). Mean barrier height was 3.46 m (SD = 4.72) but differed among regions (ANOVA: $F_{2,\ 20315}$= 1362.5, p <0.001), being higher in Scotland (barriers with height data = 8%, mean = 19.9 m, SD = 10.1) than in Wales (barriers with height data = 100%, mean = 4.78, SD = 5.92, pairwise post-hoc p <0.001) and England (barriers with height data = 100%, mean = 3.13 m, SD = 4.1, pairwise post-hoc p <0.001).

Comparisons between AMBER-GB and field survey data indicated that 68% of barriers present in the field were missing from existing records. None of the culverts, fords or ramp-bed sills found in the field were present in existing databases, whilst the presence of weirs was both under- and overestimated in existing databases, varying by region (Figure 1). Furthermore, none of the catchments surveyed during the field validation were free of artificial barriers.

The density of newly discovered barriers (i.e. those not recorded in existing databases) quickly reached an asymptote at around 0.3 barriers/km after only 68 km of river length had been surveyed (Figure 2), but the variance of the estimator did not stabilize until at least 200-250 km of river length had been sampled. The final, bootstrapped barrier discovery rate, based on 300 km of field survey, was 0.3 barriers/km (95% CI: 0.1 - 0.5).

3.2 Barrier density

Mean barrier density, based on all artificial barriers present in AMBER-GB, was 0.27 barriers/km (SE = 0.01). However, this varied by region (ANOVA: $F_{2,\ 24119} = 72.57$, p <0.001), being higher in England (mean = 0.41 barriers/km, SE = 0.02) than in Wales (mean = 0.29 barriers/km, SE = 0.02, pairwise post-hoc $p = 0.001$) or Scotland (mean = 0.14 barriers/km, SE = 0.01, pairwise post-hoc p <0.001; Figure 3A).

Differences in barrier density between field surveys and AMBER-GB were significant with a mean difference of +0.34 barriers/km observed in the field (95% CI: 0.13- 0.55, paired $t_{18} = -3.4$, $p = 0.003$), close to the bootstrapped estimate of 0.3, whilst no differences were detected between field and AMBER-GB between regions (ANOVA: $F_{2,\ 16} = 0.22$, $p = 0.80$). Therefore, a correction factor of +0.34 barriers/km was applied to the known density of all sub-catchments in Great Britain (Figure 3B). To generalise, this correction factor increases the number of artificial barriers in Great Britain from 23,618 to 66,381 (95% CI: 37,360-58,042) and results in an estimated barrier density of one barrier every 1.5 km of stream (or 0.61 barriers/km, 95% CI: 0.40- 0.82). In addition, by multiplying stream length per sub-catchment with estimated barrier density, we predict that artificial barriers are present in 99% of catchments by area in Great Britain, which is consistent with results from field validation.

3.2 Barrier-free length

To calculate barrier-free length (BFL), only dams and weirs were used, as other barrier types were under-represented (Figure 1). Stream fragmentation varied significantly by region (ANOVA $F_{2,21460} = 357.1$, p <0.001), being highest in England (mean BFL = 5.29 km, SE = 0.18), followed by Wales (mean BFL = 6.68 km, SE = 0.44; pairwise post-hoc p = 0.048) and Scotland (mean BFL = 12.30 km, SE = 0.96; pairwise post-hoc p <0.001). Overall, results indicate that only 3.3% of the total river network in Great Britain is fully connected (i.e. the barrier free length equals total river length; Figure 3C).

4. Discussion

The conservation of many freshwater communities depends on having well connected habitats (e.g. Abell et al., 2011; Forslund et al., 2009; Ruhi et al., 2019), but managers typically have few or no data on river connectivity to guide conservation efforts. Most studies on the impacts of artificial barriers tend to be limited to single catchments, or consider only large barriers (Cooper et al., 2017; Grill et al., 2015; Van Looy et al., 2014). Our study has generated the first, comprehensive, validated estimates of the density, typology and spatial distribution of artificial barriers across Great Britain, providing a valuable resource for river management.

Over half of the freshwater bodies in England and Wales have failed to achieve 'good' ecological status under the Water Framework Directive (EEA, 2012), partially due to loss of habitat and stream fragmentation. Understanding the true extent of barrier abundance and distribution should make it possible to estimate cumulative barrier impacts and apply more effective barrier prioritisation and mitigation tools that will aid in achieving good ecological status (Kemp and O'Hanley, 2010; King et al., 2017; Neeson et al., 2015). Existing barrier databases, combined for the first time in this study, indicate that only 3.3% of the total river length of Great Britain is unfragmented by dams and weirs, but our study suggests that this could be even lower if all barriers are considered. Of the nineteen catchments surveyed in this study, none were free of artificial barriers, and, based on the correction factor derived here, we can predict that artificial barriers are present in at least 99% of the river catchments of Great Britain. Most of these barriers (c. 80%) are low-head structures, whose cumulative impacts tend to be underestimated (Anderson et al., 2015; Fencl et al., 2015).

Our estimates of river fragmentation indicate a mean barrier-free length of just 6.8 km for Great Britain, although this varied considerably among areas; stream fragmentation was highest in England and lowest in Scotland, possibly reflecting current and historical differences in anthropogenic pressures (Bishop and Muñoz-Salinas, 2013; Grizzetti et al., 2017). This finding is consistent with reports that indicate that rivers in Scotland have double the length of unaltered channels (28.0 %) than those in England and Wales (13.6%; Raven, 1998; Seager et al., 2012).

Our study highlights the merits, and need, for ground-truthing estimates of stream fragmentation through field surveys, as existing databases underestimated barrier density by 68% mostly due to the presence of low-head structures. In broad terms, we were able to correct for this underestimation through simple field validation surveys where differences in barrier density between field data and AMBER-GB reached an asymptote after 68 km of sampling. However, upper and lower barrier density confidence estimates varied five-fold, even after 300 km of river length was surveyed, illustrating the need to sample a sufficient length of river to reduce uncertainty on barrier density estimates.

The database presented here (AMBER-GB) unifies barriers of different types and sources from existing databases and can be used to inform a better assessment of the global impact of stream fragmentation on fish assemblages and other taxa, based on barrier density and location (Cooper et al., 2017; King et al., 2017; Van Looy et al., 2014). The results of these studies demonstrate the value of databases on barrier location, particularly when barrier databases often lack important attributes such as barrier type, age, reservoir size, fish pass type and height (Januchowski-Hartley et al., 2019). Current estimates of barrier height are derived from remote sensing techniques (e.g. LiDAR), but these tend to be inaccurate when they are compared with field data (R^2 = 0.39, (Entec UK Ltd, 2010) and would greatly benefit from ground-truthing or better modelling. More accurate data on barrier traits may be obtained from novel assessment techniques (Diebel et al., 2015; Fuller et al., 2015; Rincón et al., 2017), which should provide a better understanding of cumulative barrier impacts, which is necessary to restore stream connectivity (Schmitt et al., 2018a).

Our results show the importance of validating existing barrier databases to estimate barrier density. However, our field validation focused on first to fourth order stream reaches delineated at the relative coarse resolution of the Ecrins river network (EEA, 2012) and restricted to areas below 340 m elevation due to access constraints. Although this may have introduced an upward bias on the number of barriers, this is relatively small (<8000) and well within the estimated 95% confidence intervals. The reaches surveyed in this study only represent 0.2% of the total river length of Great Britain, but this extent of coverage is similar to that achieved by other large scale ecological studies (Newbold et al., 2015). Crucially, our bootstrapping analyses indicate that the confidence intervals converge after c. 120 km of surveying, indicating that our reach selection criteria produced a representative sample. However, whilst our study was able to produce estimates of barrier density and stream fragmentation in Great Britain, information on barrier attributes remains patchy. In this sense, barrier data gathered by unmanned aerial vehicles (Ortega-Terol et al., 2014), modelling (Januchowski-Hartley et al., 2013; Kroon and Phillips, 2016) and volunteers in the field (Ellwood et al., 2017; Swanson et al., 2016) through a smart phone application (https://portal.amber.international/, accessed: 25/01/2019), could be used to bridge data gaps, complement existing databases, and reduce uncertainty.

5. Conclusion

Our assessment of stream fragmentation in Great Britain indicates that existing barrier databases underestimate true barrier occurrence, particularly low-head structures, by nearly a factor of 3. Using simple field surveying methods, we show how correction factors can be derived to obtain more realistic values for barrier density. Our results indicate that most catchments in Great Britain are heavily fragmented, and none or very few are free of artificial barriers. These findings provide a much needed critical starting point for assessing the true impacts of stream fragmentation across ecologically relevant spatial scales.

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References

Abell, R., Thieme, M., Lehner, B., 2011. Indicators for assessing threats to freshwater biodiversity from humans and human-shaped landscapes, in: Human Population. Springer, pp. 103–124.

Affum-baffoe, K., Baker, T.R., Lewis, S.L., Lopez-gonzalez, G., Sonke, B., Djuikouo, K., Ojo, L.O., Phillips, O.L., Reitsma, J.M., White, L., Comiskey, J.A., Ewango, C.E.N., Feldpausch, T.R., Hamilton, A.C., Gloor, M., Hart, T., Hladik, A., Lloyd, J., Lovett, J.C., Makana, J., Malhi, Y., Mbago, F.M., Ndangalasi, H.J., 2009. Increasing carbon storage in intact African tropical forests. Nature 457. https://doi.org/10.1038/nature07771

Anderson, D., Moggridge, H., Warren, P., Shucksmith, J., 2015. The impacts of ‘run-of-river’hydropower on the physical and ecological condition of rivers. Water Environ. J. 29, 268–276.

Benejam, L., Saura-Mas, S., Bardina, M., Solà, C., Munné, A., García-Berthou, E., 2016. Ecological impacts of small hydropower plants on headwater stream fish: from individual to community effects. Ecol. Freshw. Fish 25, 295–306. https://doi.org/10.1111/eff.12210

Berga, L., Buil, J.M., Bofill, E., De Cea, J.C., Perez, J.A.G., Mañueco, G., Polimon, J., Soriano, A., Yagüe, J., 2006. Dams and Reservoirs, Societies and Environment in the 21st Century, Two Volume Set: Proceedings of the International Symposium on Dams in the Societies of the 21st Century, 22nd International Congress on Large Dams (ICOLD), Barcelona, Spain, 18 June 2006. CRC Press.

Birnie-Gauvin, K., Aarestrup, K., Riis, T.M.O., Jepsen, N., Koed, A., 2017. Shining a light on the loss of rheophilic fish habitat in lowland rivers as a forgotten consequence of barriers, and its implications for management. Aquat. Conserv. Mar. Freshw. Ecosyst.

27, 1345–1349. https://doi.org/https://doi.org/10.1002/aqc.2795

Bishop, P., Muñoz-Salinas, E., 2013. Tectonics, geomorphology and water mill location in Scotland, and the potential impacts of mill dam failure. Appl. Geogr. 42, 195–205. https://doi.org/10.1016/J.APGEOG.2013.04.010

Bond, N.R., 2004. Spatial variation in fine sediment transport in small upland streams: the effects of flow regulation and catchment geology. River Res. Appl. 20, 705–717. https://doi.org/10.1002/rra.787

Bourne, C.M., Kehler, D.G., Wiersma, Y.F., Cote, D., 2011. Barriers to fish passage and barriers to fish passage assessments: the impact of assessment methods and assumptions on barrier identification and quantification of watershed connectivity. Aquat. Ecol. 45, 389–403. https://doi.org/10.1007/s10452-011-9362-z

Buddendorf, W.B., Jackson, F.L., Malcolm, I.A., Millidine, K.J., Geris, J., Wilkinson, M.E., Soulsby, C., 2019. Integration of juvenile habitat quality and river connectivity models to understand and prioritise the management of barriers for Atlantic salmon populations across spatial scales. Sci. Total Environ. 655, 557–566. https://doi.org/https://doi.org/10.1016/j.scitotenv.2018.11.263

Callow, J.N., Smettem, K.R.J., 2009. The effect of farm dams and constructed banks on hydrologic connectivity and runoff estimation in agricultural landscapes. Environ. Model. Softw. 24, 959–968.

Chao, A., Wang, Y.T., Jost, L., 2013. Entropy and the species accumulation curve: a novel entropy estimator via discovery rates of new species. Methods Ecol. Evol. 4, 1091–1100.

Compton, R.I., Hubert, W.A., Rahel, F.J., Quist, M.C., Bower, M.R., 2008. Influences of fragmentation on three species of native warmwater fishes in a Colorado River basin headwater stream system, Wyoming. North Am. J. Fish. Manag. 28, 1733–1743. https://doi.org/10.1577/M07-226.1

Cooper, A.R., Infante, D.M., Daniel, W.M., Wehrly, K.E., Wang, L., Brenden, T.O., 2017. Assessment of dam effects on streams and fish assemblages of the conterminous USA. Sci. Total Environ. 586, 879–889. https://doi.org/10.1016/J.SCITOTENV.2017.02.067

Crosa, G., Castelli, E., Gentili, G., Espa, P., 2010. Effects of suspended sediments from reservoir flushing on fish and macroinvertebrates in an alpine stream. Aquat. Sci. 72, 85–95. https://doi.org/10.1007/s00027-009-0117-z

De Leeuw, J.J., Winter, H. V., 2008. Migration of rheophilic fish in the large lowland rivers Meuse and Rhine, the Netherlands. Fish. Manag. Ecol. 15, 409–415. https://doi.org/10.1111/j.1365-2400.2008.00626.x

Diebel, M.W., Fedora, M., Cogswell, S., O'Hanley, J.R., 2015. Effects of road crossings on habitat connectivity for stream-resident fish. River Res. Appl. 31, 1251–1261. https://doi.org/10.1002/rra.2822

Ellwood, E.R., Crimmins, T.M., Miller-Rushing, A.J., 2017. Citizen science and conservation: Recommendations for a rapidly moving field. Biol. Conserv. 208, 1–4.

Entec UK Ltd, 2010. Mapping Hydropower Opportunities and Sensitivities in England and Wales. Bristol.

Environment Agency, 2018. River obstructions England and Wales. Environment Agency, Bristol.

ESRI, 2011. ArcGIS Desktop: Release 10.5. Redlands, CA Environ. Syst. Res. Inst.

European Environment Agency, 2012. EEA Catchments and Rivers Network System ECRINS v1.1. Copenhagen.

Fencl, J.S., Mather, M.E., Costigan, K.H., Daniels, M.D., 2015. How big of an effect do small dams have? Using geomorphological footprints to quantify spatial impact of low-head dams and identify patterns of across-dam variation. PLoS One 10, e0141210. https://doi.org/10.1371/journal.pone.0141210

Forslund, A., Renöfält, B.M., Barchiesi, S., Cross, K., Davidson, S., Farrell, T., Korsgaard, L., Krchnak, K., McClain, M., Meijer, K., 2009. Securing water for ecosystems and human well-being: The importance of environmental flows. Swedish Water House Rep. 24.

Forzieri, G., Gardenti, M., Caparrini, F., Castelli, F., 2008. A methodology for the pre-selection of suitable sites for surface and underground small dams in arid areas: A case study in the region of Kidal, Mali. Phys. Chem. Earth, Parts A/B/C 33, 74–85. https://doi.org/10.1016/J.PCE.2007.04.014

Frings, R.M., Vaeßen, S.C.K., Groß, H., Roger, S., Schüttrumpf, H., Hollert, H., 2013. A fish-passable barrier to stop the invasion of non-indigenous crayfish. Biol. Conserv. 159, 521–529. https://doi.org/10.1016/J.BIOCON.2012.12.014

Fuller, M.R., Doyle, M.W., Strayer, D.L., 2015. Causes and consequences of habitat fragmentation in river networks. Ann. N. Y. Acad. Sci. 1355, 31–51.

Garcia de Leaniz, C., 2008. Weir removal in salmonid streams: Implications, challenges and practicalities. Hydrobiologia 609, 83–96. https://doi.org/10.1007/s10750-008-9397-x

Garcia de Leaniz, C., Belletti, B., Bizzi, S., Segura, G., Borger, L., Jones, J., Olivo del Amo, R., Wanningen, H., Tummers, J., Kerr, J., Kemp, P., van de Bund, W., the AMBER consortium, 2018. The importance of having a good database for restoring river connectivity: the AMBER Barrier Atlas in Europe, in: Brink, K., Gough, P., Royte, J., Schollema, P.P., Wanningen, H. (Eds.), From Sea to Source 2.0. Protection and Restoration of Fish Migration in Rivers Worldwide. World Fish Migration Foundation, Groningen, pp. 142–145.

Garcia de Leániz, C., van de Bund, W., Bizzi, S., Belletti, B., Zalewski, M., Krauze, K., Parasiewicz, P., Kemp, P., Aarestrup, K., Birnie-Gauvin, K., Wanningen, H., van Deelen, J., Olivo del Amo, R., Dodkins, I., 2018. Periodic Technical Report Part B.

Gauld, N.R., Campbell, R.N.B., Lucas, M.C., 2013. Reduced flow impacts salmonid smolt emigration in a river with low-head weirs. Sci. Total Environ. 458, 435–443.

Gibson, R.J., Haedrich, R.L., Wernerheim, C.M., 2011. Loss of fish habitat as a consequence of inappropriately constructed stream crossings. Chang. Publ. Wiley 30, 10–17. https://doi.org/10.1577/1548-8446(2005)30[10:LOFHAA]2.0.CO;2

Gomes, P.I.A., Wai, O.W.H., Yan, X.-F., 2017. Eco-hydraulic evaluation of herbaceous ecosystems below headwater dams without a base flow: Observing below dam reaches as new stream sources. Ecohydrology 10, e1774. https://doi.org/10.1002/eco.1774

Grill, G., Lehner, B., Lumsdon, A.E., MacDonald, G.K., Zarfl, C., Liermann, C.R., 2015. An index-based framework for assessing patterns and trends in river fragmentation and flow regulation by global dams at multiple scales. Environ. Res. Lett. 10, 15001.

Grizzetti, B., Pistocchi, A., Liquete, C., Udias, A., Bouraoui, F., van de Bund, W., 2017. Human pressures and ecological status of European rivers. Sci. Rep. 7, 205.

https://doi.org/10.1038/s41598-017-00324-3

Harding, D.J., Dwyer, R.G., Mullins, T.M., Kennard, M.J., Pillans, R.D., Roberts, D.T., 2017. Migration patterns and estuarine aggregations of a catadromous fish, Australian bass (Percalates novemaculeata) in a regulated river system. Mar. Freshw. Res. 68, 1544. https://doi.org/10.1071/MF16125

Hohensinner, S., Habersack, H., Jungwirth, M., Zauner, G., 2004. Reconstruction of the characteristics of a natural alluvial river–floodplain system and hydromorphological changes following human modifications: the Danube River (1812–1991). River Res. Appl. 20, 25–41.

Holthe, E., Lund, E., Finstad, B., Thorstad, E.B., McKinley, R.S., 2005. A fish selective obstacle to prevent dispersion of an unwanted fish species, based on leaping capabilities. Fish. Manag. Ecol. 12, 143–147. https://doi.org/10.1111/j.1365-2400.2004.00436.x

Januchowski-Hartley, S.R., Jézéquel, C., Tedesco, P.A., 2019. Modelling built infrastructure heights to evaluate common assumptions in aquatic conservation. J. Environ. Manage. 232, 131–137. https://doi.org/10.1016/J.JENVMAN.2018.11.040

Januchowski-Hartley, S.R., McIntyre, P.B., Diebel, M., Doran, P.J., Infante, D.M., Joseph, C., Allan, J.D., 2013. Restoring aquatic ecosystem connectivity requires expanding inventories of both dams and road crossings. Front. Ecol. Environ. 11, 211–217.

Jungwirth, M., Muhar, S., Schmutz, S., 2000. Fundamentals of fish ecological integrity and their relation to the extended serial discontinuity concept. Hydrobiologia 422, 85–97.

Keefer, M.L., Caudill, C.C., 2016. Estimating thermal exposure of adult summer steelhead and fall Chinook salmon migrating in a warm impounded river. Ecol. Freshw. Fish 25, 599–611. https://doi.org/10.1111/eff.12238

Kemp, P.S., O’Hanley, J.R., 2010. Procedures for evaluating and prioritising the removal of fish passage barriers: a synthesis. Fish. Manag. Ecol. 17, 297–322.

King, S., O’Hanley, J.R., Newbold, L.R., Kemp, P.S., Diebel, M.W., 2017. A toolkit for optimizing fish passage barrier mitigation actions. J. Appl. Ecol. 54, 599–611.

Kroon, F.J., Phillips, S., 2016. Identification of human-made physical barriers to fish passage in the Wet Tropics region, Australia. Mar. Freshw. Res. 67, 677–681.

Lehner, B., Liermann, C.R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., Döll, P., Endejan, M., Frenken, K., Magome, J., Nilsson, C., Robertson, J.C., Rödel, R., Sindorf, N., Wisser, D., 2011. High-resolution mapping of the world’s reservoirs and dams for sustainable river-flow management. Front. Ecol. Environ. 9, 494–502. https://doi.org/10.1890/100125

Lempérière, F., 2017. Dams and Floods. Engineering 3, 144–149. https://doi.org/10.1016/J.ENG.2017.01.018

Mantel, S.K., Hughes, D.A., Muller, N.W.J., 2010a. Ecological impacts of small dams on South African rivers Part 1: drivers of change-water quantity and quality. Water Sa 36, 351–360.

Mantel, S.K., Muller, N.W.J., Hughes, D.A., 2010b. Ecological impacts of small dams on South African rivers Part 2: biotic response-abundance and composition of macroinvertebrate communities. Water Sa 36, 361–370.

Mantel, S.K., Rivers-Moore, N., Ramulifho, P., 2017. Small dams need consideration in riverscape conservation assessments. Aquat. Conserv. Mar. Freshw. Ecosyst. 27, 748–

754.

McCarthy, T.K., Frankiewicz, P., Cullen, P., Blaszkowski, M., O'connor, W., Doherty, D., 2008. Long-term effects of hydropower installations and associated river regulation on River Shannon eel populations: mitigation and management. Hydrobiologia 609, 109–124.

Meixler, M.S., Bain, M.B., Walter, M.T., 2009. Predicting barrier passage and habitat suitability for migratory fish species. Ecol. Modell. 220, 2782–2791.

Mueller, M., Pander, J., Geist, J., 2011. The effects of weirs on structural stream habitat and biological communities 48, 1450–1461. https://doi.org/10.1111/j.1365-2664.2011.02035.x

Muth, R., Crist, L., LaGory, K., Hayse, J., Bestgen, K., Ryan, T., Lyons, J., Valdez, R., 2000. Flow and temperature recommendations for endangered fishes in the Green River downstream of Flaming Gorge Dam.

Neeson, T.M., Ferris, M.C., Diebel, M.W., Doran, P.J., O'Hanley, J.R., McIntyre, P.B., 2015. Enhancing ecosystem restoration efficiency through spatial and temporal coordination. Proc. Natl. Acad. Sci. 201423812.

Newbold, T., Hudson, L.N., Hill, S.L.L., Contu, S., Lysenko, I., Senior, R.A., Börger, L., Bennett, D.J., Choimes, A., Collen, B., 2015. Global effects of land use on local terrestrial biodiversity. Nature 520, 45–50.

Nyqvist, D., Greenberg, L.A., Goerig, E., Calles, O., Bergman, E., Ardren, W.R., Castro-Santos, T., Castro-Santos, T., 2017. Migratory delay leads to reduced passage success of Atlantic salmon smolts at a hydroelectric dam. Ecol. Freshw. Fish 26, 707–718. https://doi.org/10.1111/eff.12318

Ortega-Terol, D., Moreno, M., Hernández-López, D., Rodríguez-Gonzálvez, P., 2014. Survey and classification of Large Woody Debris (LWD) in streams using generated low-cost geomatic products. Remote Sens. 6, 11770–11790.

Petts, G.E., Gurnell, A.M., 2005. Dams and geomorphology: Research progress and future directions. Geomorphology 71, 27–47. https://doi.org/10.1016/J.GEOMORPH.2004.02.015

QGIS Development Team, 2018. QGIS Geographic Information System. Open Source Geospatial Foundation Project.

Quinlan, E., Gibbins, C.N., Batalla, R.J., Vericat, D., 2015. Impacts of Small Scale Flow Regulation on Sediment Dynamics in an Ecologically Important Upland River. Environ. Manage. 55, 671–686. https://doi.org/10.1007/s00267-014-0423-7

R Core Team, 2018. R: A language and environment for statistical computing.

Raven, P.J., 1998. River Habitat Quality: the physical character of rivers and streams in the UK and Isle of Man. Environment Agency.

Rincón, G., Solana-gutiérrez, J., Alonso, C., Santiago Saura, ·, García De Jalón, D., Solana-Gutiérrez, J., Alonso, C., Saura, S., de Jalón, D.G., 2017. Longitudinal connectivity loss in a riverine network: accounting for the likelihood of upstream and downstream movement across dams. Aquat. Sci. 79, 573–585. https://doi.org/10.1007/s00027-017-0518-3

Rojanamon, P., Chaisomphob, T., Bureekul, T., 2009. Application of geographical information system to site selection of small run-of-river hydropower project by considering engineering/economic/environmental criteria and social impact. Renew.

Sustain. Energy Rev. 13, 2336–2348. https://doi.org/10.1016/J.RSER.2009.07.003

Rolls, R.J., 2011. The role of life-history and location of barriers to migration in the spatial distribution and conservation of fish assemblages in a coastal river system. Biol. Conserv. 144, 339–349.

Rolls, R.J., Ellison, T., Faggotter, S., Roberts, D.T., 2013. Consequences of connectivity alteration on riverine fish assemblages: potential opportunities to overcome constraints in applying conventional monitoring designs. Aquat. Conserv. Mar. Freshw. Ecosyst. 23, 624–640. https://doi.org/10.1002/aqc.2330

Ruhi, A., Catford, J.A., Cross, W.F., Escoriza, D., Olden, J.D., 2019. Understanding the nexus between hydrological alteration and biological invasions, in: Multiple Stressors in River Ecosystems. Elsevier, pp. 45–64.

Russon, I.J., Kemp, P.S., Lucas, M.C., 2011. Gauging weirs impede the upstream migration of adult river lamprey Lampetra fluviatilis. Fish. Manag. Ecol. 18, 201–210.

Schmitt, R.J.P., Bizzi, S., Castelletti, A., Kondolf, G.M., 2018a. Improved trade-offs of hydropower and sand connectivity by strategic dam planning in the Mekong. Nat. Sustain. 1, 96–104. https://doi.org/10.1038/s41893-018-0022-3

Schmitt, R.J.P., Bizzi, S., Castelletti, A.F., Kondolf, G.M., 2018b. Stochastic modeling of sediment connectivity for reconstructing sand fluxes and origins in the unmonitored Se Kong, Se San, and Sre Pok tributaries of the Mekong River. J. Geophys. Res. Earth Surf. 123, 2–25. https://doi.org/10.1002/2016JF004105

Seager, K., Baker, L., Parsons, H., Raven, P., Vaughan, I.P., 2012. The rivers and streams of England and Wales: an overview of their physical character in 2007–2008 and changes since 1995–1996. River Conserv. Manag. 27–41.

SEPA, 2018. Scottish Obstacles to Fish Migration data set [WWW Document]. URL https://www.sepa.org.uk/environment/environmental-data/ (accessed 9.10.18).

Spedicato, M.T., Lembo, G., Marmulla, G., 2005. Upstream migration of Atlantic salmon in three regulated rivers, in: Aquatic Telemetry: Advances and Applications: Proceedings of the Fifth Conference on Fish Telemetry Held in Europe, Ustica, Italy, 9-13 June 2003. Food & Agriculture Org., p. 111.

Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology. Eos, Trans. Am. Geophys. Union 38, 913–920.

Swanson, A., Kosmala, M., Lintott, C., Packer, C., 2016. A generalized approach for producing, quantifying, and validating citizen science data from wildlife images. Conserv. Biol. 30, 520–531.

Thorstad, E.B., Økland, F., Kroglund, F., Jepsen, N., 2003. Upstream migration of Atlantic salmon at a power station on the River Nidelva, Southern Norway. Fish. Manag. Ecol. 10, 139–146.

USACE, 2000. US Army Corps of Engineers National Inventory of Dams.

Van Looy, K., Tormos, T., Souchon, Y., 2014. Disentangling dam impacts in river networks. Ecol. Indic. 37, 10–20. https://doi.org/10.1016/J.ECOLIND.2013.10.006

Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R., Cushing, C.E., 1980. The river continuum concept. Can. J. Fish. Aquat. Sci. 37, 130–137.

Vogt, J. V, Rimaviciute, E., de Jager, A., 2008. CCM2 River and Catchment Database for

Europe: Version 2.1 Release Notes.

Ward, J. V., Stanford, J.A., 1979. The ecology of regulated streams : [proceedings of the first International Symposium on Regulated Streams held in Erie, Pa., April 18-20, 1979]. Plenum Press.

Warren, M.L., Pardew, M.G., 1998. Road crossings as barriers to small-stream fish movement. Trans. Am. Fish. Soc. 127, 637–644. https://doi.org/10.1577/1548-8659(1998)127<0637:RCABTS>2.0.CO;2

WCD, 2000. Dams and Development: A New Framework for Decision-making: the Report of the World Commission on Dams. Earthscan.

Whiteley, A.R., Hastings, K., Wenburg, J.K., Frissell, C.A., Martin, J.C., Allendorf, F.W., 2010. Genetic variation and effective population size in isolated populations of coastal cutthroat trout. Conserv. Genet. 11, 1929–1943.

Yasser, M., Jahangir, K., Mohmmad, A., 2013. Earth dam site selection using the analytic hierarchy process (AHP): a case study in the west of Iran. Arab. J. Geosci. 6, 3417–3426. https://doi.org/10.1007/s12517-012-0602-

Table 1. Barrier types included in each of the databases of artificial barriers in Great Britain combined in this study (AMBER-GB).

		Barrier types included in each database matched to European Barrier Atlas categories							*Proportion included in AMBER-GB*	*Source*
Database	*Region*	*Dam*	*Weir*	*Sluice*	*Culvert*	*Ford*	*Ramp-bed sill*	*Other*		
EA	England and Wales	dam	weir	barrage, sluice, lock	culvert	ford		null, unknown, mill, other	0.998	EA, 2018
SEPA	Scotland	dam	weir	sluice, lock, water gate	culvert, pipe bridge	ford	bridge apron	unknown, screen, wall, intake, artificial cascade, flume, fish trap, fish scarer	0.965	SEPA, 2018
GRanD	Global	dam	-	-	-	-	-	-	1.000	Lehner et al., 2011
Ecrins	Europe	dam	-	-	-	-	-	-	0.856	EEA, 2012

Table 2. Summary of barrier type, abundance and height for England, Scotland and Wales. No available barrier height information is denoted by 'NA'.

				Barrier height (m)	
Region	*Barrier type*	*n*	*%*	*mean (μ)*	*standard deviation (σ^2)*
England	culvert	8	0.04	NA	NA
	dam	705	3.70	12.02	12.84
	ford	2	0.01	NA	NA
	ramp-bed sill	1	0.01	NA	NA
	sluice	2712	14.23	2.29	1.45
	weir	14945	78.44	2.86	2.85
	other	680	3.57	1.84	1.44
	total	19053	-	3.13	4.10
Scotland	culvert	258	12.12	0.75	NA
	dam	469	22.04	20.90	9.32
	ford	57	2.68	NA	NA
	ramp-bed sill	91	4.28	NA	NA
	sluice	52	2.44	NA	NA
	weir	744	34.96	1.12	0.99
	other	457	21.48	NA	NA
	total	2128	-	19.90	10.10
Wales	dam	169	6.93	13.43	15.81
	sluice	163	6.69	3.93	2.02
	weir	1954	80.18	4.16	3.51
	other	151	6.20	3.66	4.09
	total	2437	-	4.78	5.92
Great Britain	total	23618	-	3.46	4.72

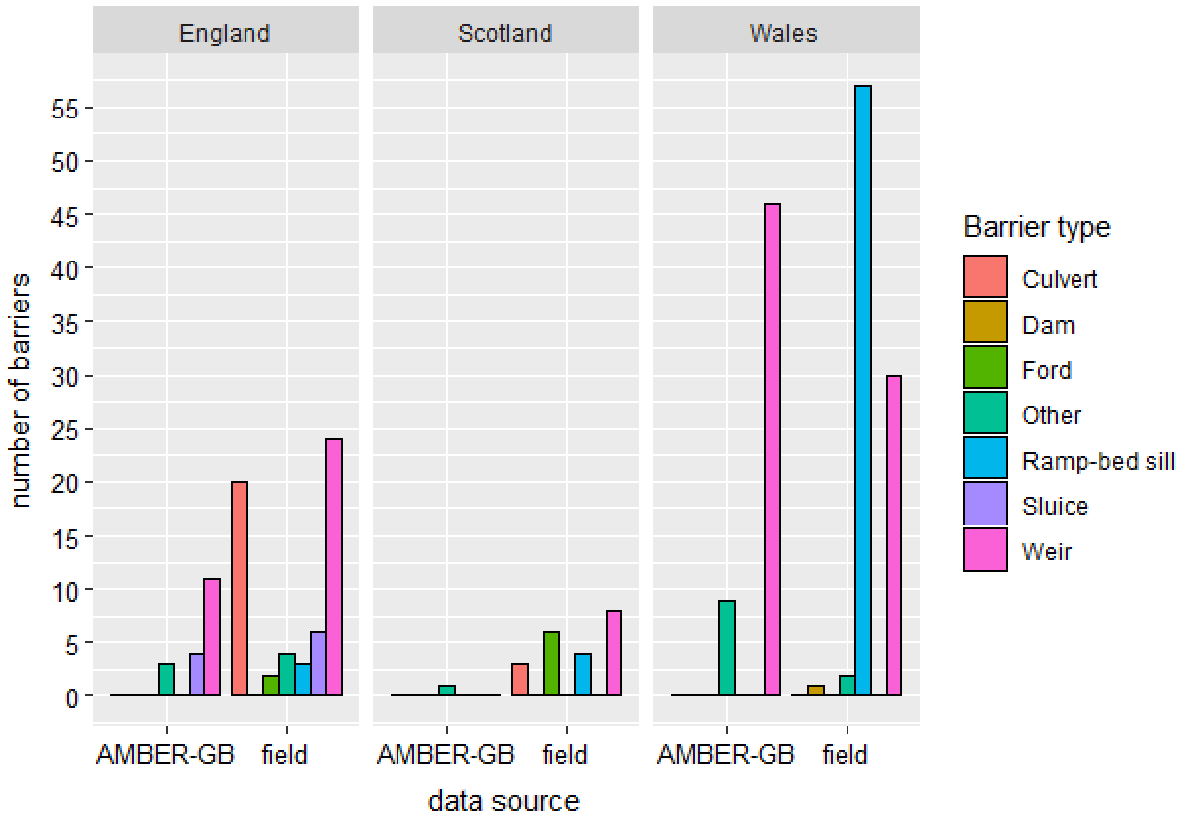

Figure 1. Barrier types observed in the field validation and recorded in existing barrier databases for the same reaches. Total river length surveyed in England was 84 km, 113 km in Scotland and 106 km in Wales.

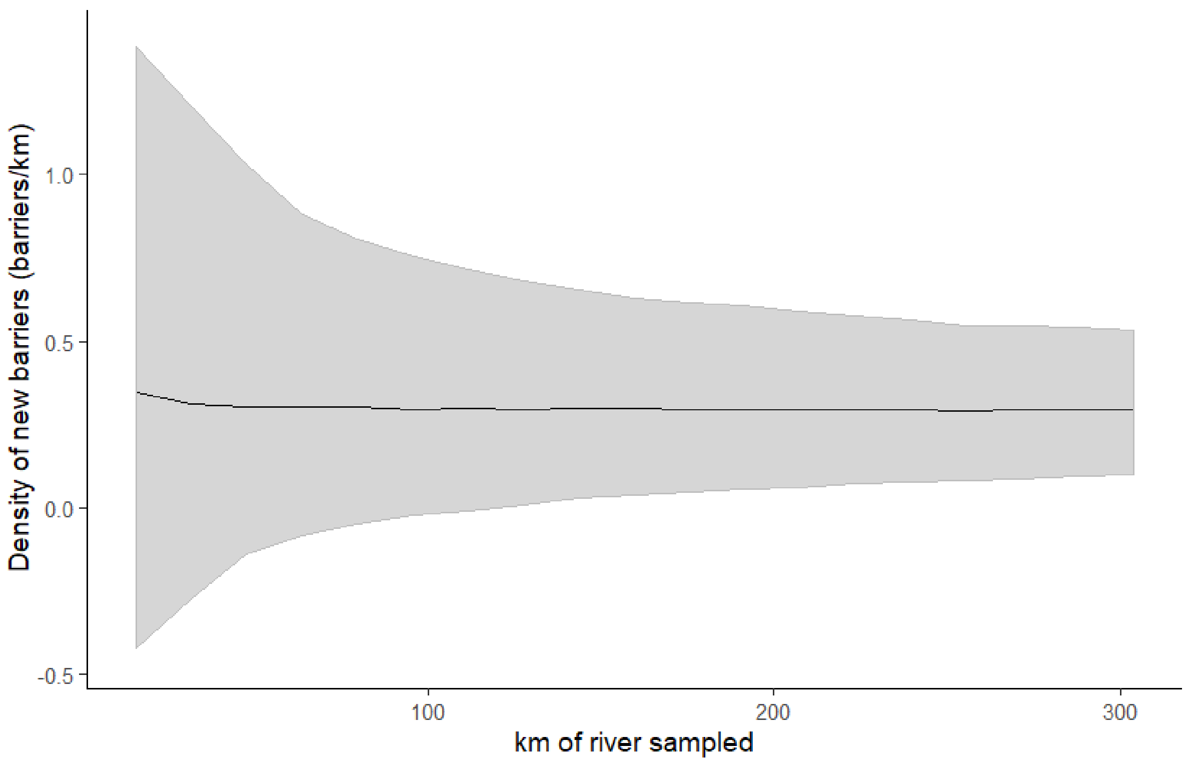

Figure 2. Bootstrapped density of new barriers with 95% CI absent from AMBER-GB as observed in 19 catchments in England, Scotland and Wales during walkover surveys ranging from 1.9 km to 30.3 km.

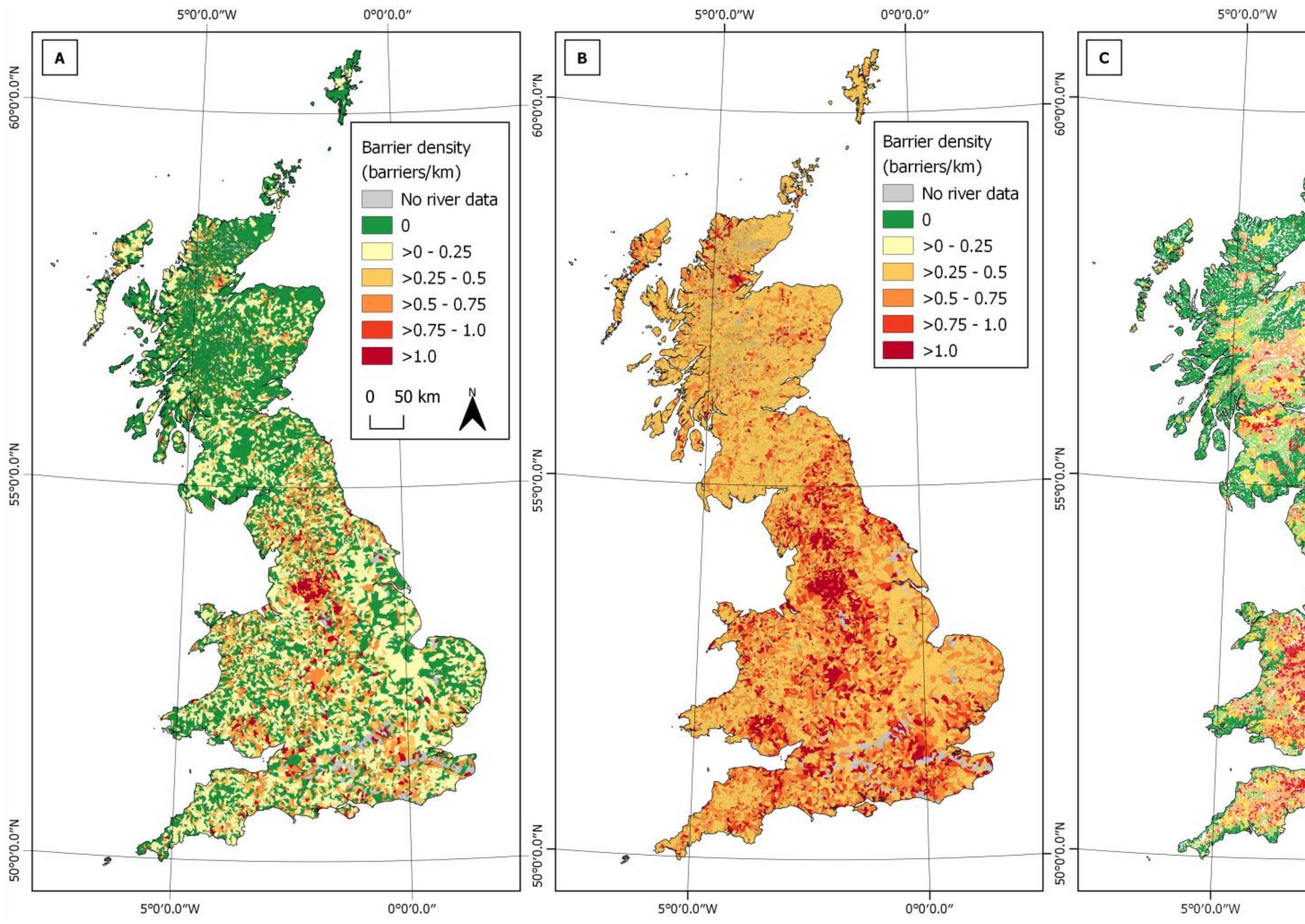

Figure 3. A) Existing records of barrier density (*barriers/km*) in Great Britain at CCM 2.1 catchment scale (*co*
Agency, Scottish Environmental Protection Agency, GRanD and Ecrins barrier databases and OS Open Rivers
density corrected by data from field barrier surveys across 19 catchments (303 km). C) Barrier-free len
network length in Great Britain based on records of dams and weirs.

Figure S1. Distribution of 19 rivers surveyed during field validation in England (n = 5), Scotland (n = 9) and Wales (n = 5).

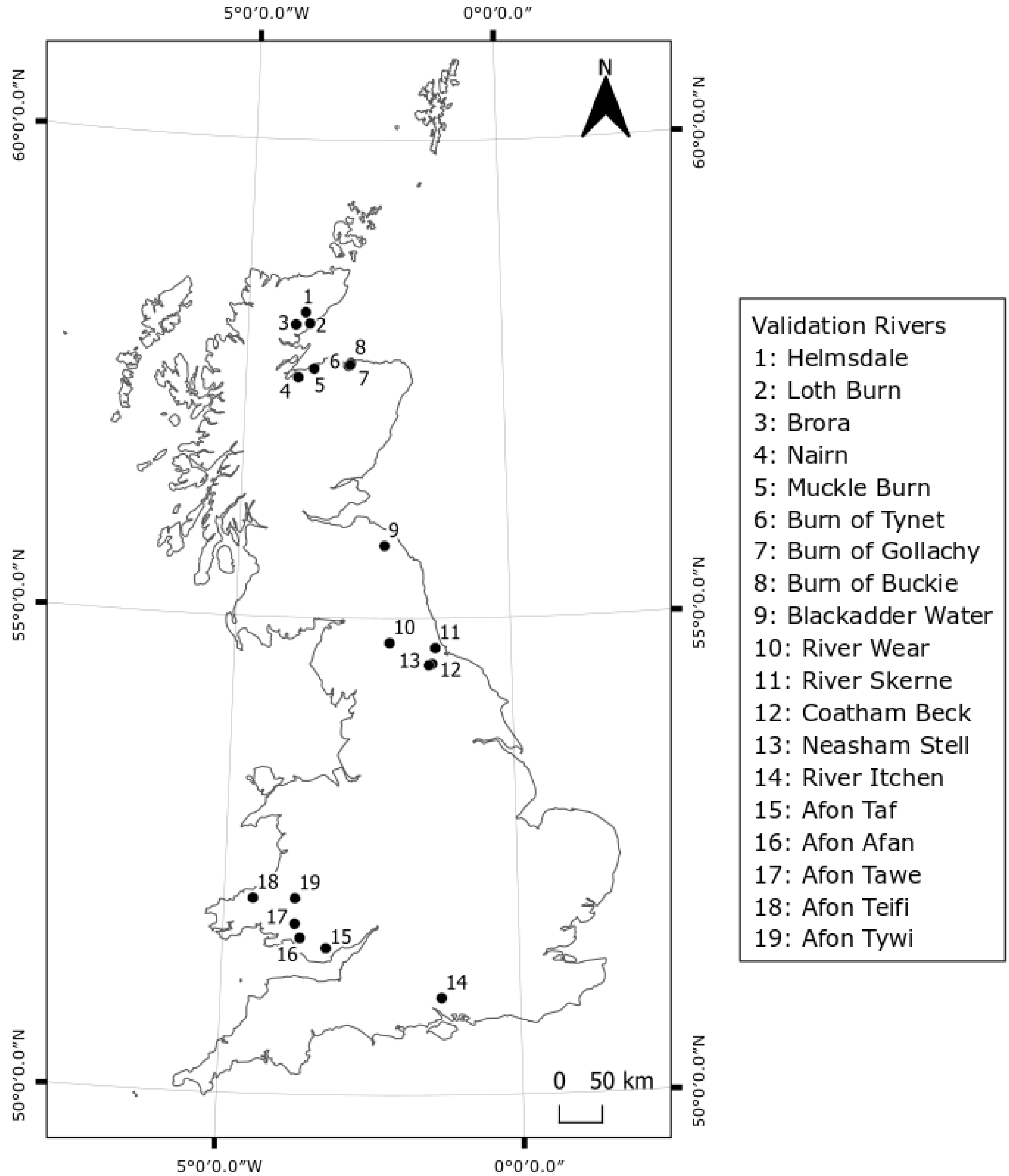

Table S1. Summary of 19 rivers surveyed during field validation in England (n = 5), Scotland (n = 9) and Wale

ID	*River*	*Reach*	*Length (m)*	*Mean altitude (m)*	*Mean slope (%)*	*Number of channels*	*Sinuosity*	*CORINE land c*
1	Helmsdale	downstream	15146	57	0.5	1	1.3	agricultural ar
		upstream	15163	103	0.3	1	1.13	forests and se areas
2	Loth Burn	both	3638	68	3.7	1	1.19	forests and se areas
3	Brora	both	14954	79	0.9	1	1.3	agricultural ar
4	Nairn	downstream	12692	39	0.5	1	1.09	agricultural ar
		upstream	12685	114.5	0.8	1	1.09	agricultural ar
5	Muckle Burn	both	4083	16.5	0.2	1	1.3	agricultural ar
6	Burn of Tynet	both	7400	82.5	3.3	1	1.33	agricultural ar
7	Burn of Gollachy	both	5457	84.5	3.1	1	1.12	agricultural ar
8	Burn of Buckie	both	1849	19.5	2.6	1	1.21	artificial surfa
9	Blackadder Water	downstream	9600	58.4	0.3	1	1.54	agricultural ar
		upstream	10415	86.9	0.6	1	1.28	agricultural ar
10	River Wear	downstream	10268	259.2	0.9	1	1.07	agricultural ar
		upstream	9996	346.3	1.6	1	1.25	agricultural ar
11	River Skerne	downstream	8504	69.4	1.1	1	1.33	forests and se areas
		upstream	10796	93.8	0.9	1	1.31	forests and se areas
12	Coatham Beck	downstream	10562	49.5	0.4	1	1.43	agricultural ar
13	Neasham Stell	upstream	11212	22.5	0.2	1	1.44	agricultural ar
14	River Itchen	downstream	8734	24.5	0.17	>1	1.42	agricultural ar
		upstream	13600	53.5	0.17	>1	1.31	agricultural ar

15	Afon Taf	downstream	11200	16	0.16	1	1.21	artificial surfa
		upstream	11200	36.5	0.17	1	1.15	artificial surfa
16	Afon Afan	downstream	11200	46.5	1.01	1	1.12	artificial surfa
		upstream	11200	192.9	2.11	1	1.08	forests and se areas
17	Afon Tawe	downstream	11500	67.9	0.82	1	1.19	artificial surfa
		upstream	11500	288.2	3.4	1	1.05	forests and se areas
18	Afon Teifi	downstream	8322	14.6	0.2	1	1.41	forests and se areas
		upstream	8322	27.3	0.1	1	1.62	forests and se areas
19	Afon Tywi	downstream	10670	79.5	0.47	1	1.14	forests and se areas
		upstream	10670	149.7	1.78	1	1.32	forests and se areas

Table S2. Comparison of field validation reaches to all catchments in Great Britain.

	field		Great Britain					
	median	IQR	median	IQR	χ^2	W	P	Test
Stream order (Strahler)	3	2	1	1	-	114070	<0.001	
Slope (%)	0.7	1.3	4.9	9.3	-	24855	<0.001	Wilcoxon
Elevation (m)	68	54.9	43.4	114	-	77246	0.056	
Land cover (CORINE Level 1)	2	1	2	1	0.46	-	0.447	Kruskal-Wallis